

Explosions and Outflows during Galaxy Formation

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Abstract. We consider an explosion at the center of a halo which forms at the intersection of filaments inside a cosmological pancake, a convenient test-bed model for galaxy formation. ASPH/P³M simulations reveal that such explosions are anisotropic. The energy and metals are channeled into the low density regions, away from the pancake. The pancake remains essentially undisturbed, even if the explosion is strong enough to blow away all the gas located inside the halo and reheat the IGM surrounding the pancake. Infall quickly replenishes this ejected gas and gradually restores the gas fraction as the halo continues to grow. Estimates of the collapse epoch and SN energy-release for galaxies of different mass in the CDM model can relate these results to scale-dependent questions of blow-out and blow-away and their implication for early IGM heating and metal enrichment and the creation of gas-poor dwarf galaxies.

INTRODUCTION

The release of energy that occurs during galaxy formation can have important consequences. We present 3D gas dynamical simulations of the effect of energy release by supernovae (SNe) on the evolution of the halo in which the explosions take place, the surrounding large-scale structure, and the IGM.

Structure formation from Gaussian random noise is highly anisotropic, favoring pancakes and filaments over quasi-spherical objects. However, pancake fragmentation results in the formation of quasi-spherical halos [1,2,6,8] with density profiles similar to the universal profile [7] found in CDM simulations. This suggests that pancake fragmentation may be used to study galaxy formation. This provides a good compromise between simulations of structure formation in CDM models, with limited resolution, and those of isolated virialized objects, which ignore cosmological initial and boundary conditions. We use our ASPH/P³M method to simulate the formation of a halo at the intersection of two filaments in the plane of a cosmological pancake which collapses at scale factor $a = a_c$, in an $\Omega_0 = 1$ universe with baryon fraction $\Omega_B = 0.03$ (see [3,4] for further description). These simulations also describe early galaxy formation in a flat, Λ CDM model. The explosion is induced at scale factor $a_{\text{exp}}/a_c \cong 2$, when the central gas density first exceeds

$\rho_{\text{gas}}/\langle\rho_{\text{gas}}\rangle = 1000$, by boosting the thermal energy of this central gas to the level $E_{\text{exp}} = \chi\mathcal{E}_{\text{halo}}$, where $\mathcal{E}_{\text{halo}}$ is the total thermal energy of gas in the halo, for four cases: $\chi = 0, 10, 100$, and 1000 .

RESULTS

Figure 1 shows the pancake-filament-halo structure at $a/a_c = 3$, with and without explosions. For all cases, the dark matter distribution is essentially the same as the gas distribution for $\chi = 0$. The pancake and filaments ensure that a highly anisotropic explosion results, channelling the energy and mass ejection along the symmetry axis. The ability of explosions to eject metal-enriched gas depends on χ .

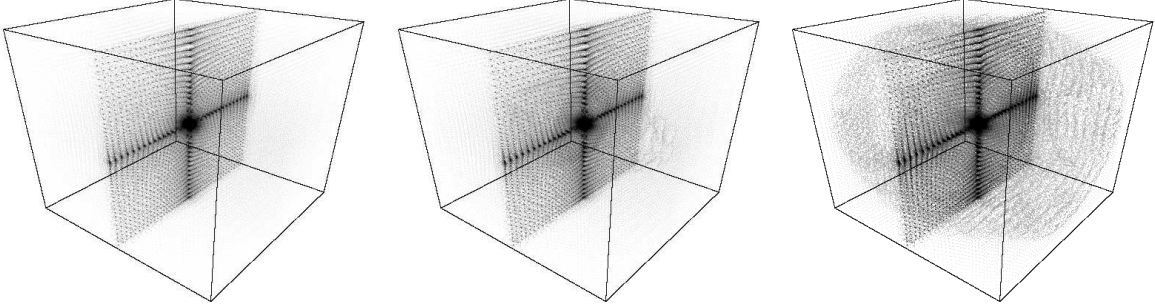


FIGURE 1. Gas distribution at $a/a_c = 3$. (left) no explosion case ($\chi = 0$); (middle) explosion case with $\chi = 100$; (right) explosion case with $\chi = 1000$.

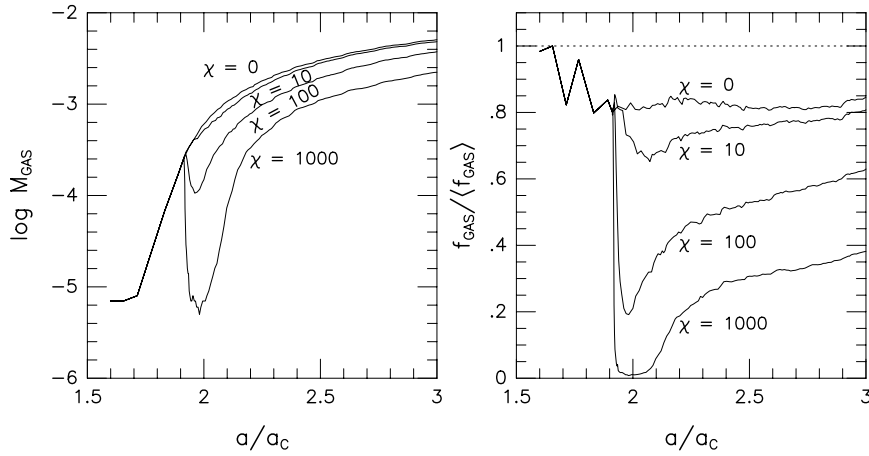


FIGURE 2. (Left) gas mass M_{gas} (in computational units $M_{\text{box}} = \bar{\rho}\lambda_p^3 = 1$) in the central halo (sphere of mean overdensity 200), versus a/a_c , for different explosion intensities, as labelled. (Right) gas mass fraction f_{gas} inside halo, divided by the universal gas mass fraction $\langle f_{\text{gas}} \rangle = \Omega_B/\Omega_0$, versus a/a_c .

For $\chi = 10$, relatively little gas is blown out of the halo, and is quickly re-accreted. For $\chi > 100$, most of the halo gas is blown out. However, as shown in Figure 2, infall along the pancake plane continues despite the explosion and replenishes the ejected halo gas very efficiently, although the final gas fraction f_{gas} is below the cosmic mean value by an amount which increases with increasing χ . Even the most energetic explosions fail to disturb the pancake and filaments.

Each dimensionless, scale-free simulation for a given χ can be applied to any particular halo mass M_{halo} at any epoch by adjusting the values of λ_p (the wavelength of the primary pancake) and collapse redshift z_c when converting to physical units. We can also use Milky Way (MW) star formation efficiencies and IMF to estimate a typical value $\chi_*(\lambda_p, z_c)$ of the explosion parameter χ , for each λ_p and z_c . $\chi \gtrsim 100$ is required to eject gas and metals into the IGM. This matches MW efficiencies only for $M_{\text{halo}} \lesssim 10^7 M_\odot$, for both cluster-normalized SCDM (i.e. $\lambda_p < 0.2$ Mpc) and COBE-normalized Λ CDM ($\Omega_0 = 0.3$, $\lambda_0 = 0.7$, $h = 0.7$) (i.e. $\lambda_p < 0.3$ Mpc). However, gas replenishment by continued infall may enable a single halo to contribute multiple outbursts. Halos $< 10^{10} M_\odot$ form early enough to cause heavy element distribution prior to $z = 3$. Only the smallest mass objects, however, can expect to do so if limited to MW efficiencies. Such small mass halos are also the ones which are most likely to form early enough that they may explode *before* the reionization of the IGM is complete, after which the enhanced IGM pressure inhibits gas ejection. Otherwise efficiencies greatly exceeding MW values are required.

A final determination of the success or failure of heavy element distribution by SN explosions in low-mass halos forming at high redshift will depend sensitively on the efficiencies of star formation and SN energy release, and the relative timing of these explosions versus universal reionization. Our results suggest that heavy element distribution at the observed level of $\approx 10^{-3}$ solar in the IGM could have been accomplished most efficiently by low-mass objects prior to the completion of universal reionization. (NASA ATP grants NAG5-7363 and NAG5-7821, NSF grant ASC-9504046, and Texas Advanced Research Program grant 3658-0624-1999).

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